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THE ROYAL ASTRONOMICAL SOCIETY OF CANADA

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PLATE VIII

SPECTRUM OF A FIREBALL, PHOTOGRAPHED AT FLAGSTAFF, ARIZONA, FEBRUARY 26, 1933.

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SPECTRUM OF A FIREBALL, FEBRUARY 26, 1933

By Peter M. Millman

(With Plate VIII)

THE spectrum shown in Plate VIII was photographed during a systematic programme for meteor spectrophotography carried out by the writer at the Harvard Meteor Station, Flagstaff, Arizona, under a fellowship from the Royal Society of Canada. The plate was exposed by Mr. Don Hargrave of the Harvard Meteor Expedition to Arizona.

The exposure was on the north pole, being one hour in length. The camera was on a stationary mount so that the stars made circular trails about the pole. Polaris is the very bright star in the upper right, about one and a half inches from the edge. A Boyer lens of six-inch focal length and focal ratio of 4.5 was used. A 30-degree Hilger prism was mounted before the lens so that the stellar images are drawn out into little spectra. The dispersion is horizontal with the violet end of the spectrum to the left, the red end to the right. The hydrogen lines are clearly visible in the star at the extreme right.

The fireball itself appeared at $23^h\,35^m\,23^s$, M.S.T., on February 26, 1933. Its trail starts at the upper left and proceeds down and towards the centre of the plate. Marked flickering of the fireball is noted along the length of the trail with a final brilliant burst at the end. The visual magnitude at this point was estimated to be —9, or approximately fifty times the brightness of Venus at her greatest

brilliancy. The fireball was observed and plotted at the second station, 22 miles from Flagstaff, which makes it possible to compute the height. The trail visible on the plate extended approximately from an altitude of 125 km. to one of 80 km. The bright final burst occurred at a height of 94 km.

This spectrum shows the greatest detail of any photographed to date, 63 bright lines having been measured, and it will probably give us more information about meteors than any other single photograph yet obtained. The lines in the spectrum prove to be given almost entirely by iron vapor at very low excitation. The plate used was the Cramer Iso Presto so that the right end of the spectrum includes lines in the yellow-green. A complete discussion of this object will be published later in the Harvard Annals.

NOVA OPHIUCHI No. 3—1744*06*

By H. Boyd Brydon

THE faint star RS Ophiuchi, the third nova in this constellation, quiescent since its outburst in 1898, suddenly increased to a new maximum in August last, reaching magnitude 4.3. (See the last issue of this Journal, p. 337.)

This star, No. 162214 in the Henry Draper Catalogue, was given magnitude 9.5 by Schönfeld in the Southern Extension of the BD, where its number is —6.4661.

The outburst of 1898 was discussed by E. C. Pickering[1] who gave two tables of magnitudes, one containing the annual means of the magnitudes of the star from 1888 to 1905; the other, here reproduced as table I, the magnitudes from individual observations during 1898.

Table I

RS Ophiuchi, 1898

Date	Mag.	Date	Mag.	Date	Mag.
April 2	10.70	July 14	8.26	Sept. 7	10.00
May 27	10.76	July 15	8.22	Sept. 29	10.28
May 31	10.81	Aug. 15	9.27	Oct. 8	10.81
June 30	7.69	Aug. 20	9.32		

In Fig. I, which is reproduced from a paper on "Novae and Variable Stars," by Harlow Shapley[2] is shown the photographic light surve of RS Ophiuchi from 1892 to 1915. Dr. Shapley says: "This star would certainly be classed as an irregular variable were it not for its nova-like spectrum and the one sharp maximum in 1898. RS Ophiuchi lies in the rift in the Milky Way and, like many other temporary stars, appears to be in the vicinity of diffuse nebulosity. The irregularities of such objects are probably no more

[1]Harvard Circular No. 99, 1905.
[2]A.S.P. XXXIII, 1921, p. 191.

pronounced than the irregularities in the nebulous clouds through which they may be moving. It is probable that many old novae and the miniature novae of the RS Ophiuchi type do exist at the present time as irregular variable stars."

The Reports of the AAVSO[3] contain no observations of this star between 1912, the earliest available, and 1921, except one by Grey, magnitude 11.0 on JD 2420299 and one by Eaton, magnitude 11.5 on JD 2422353.

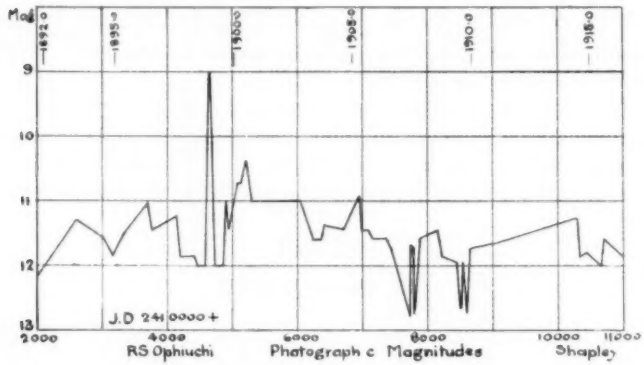

Fig. 1. Photographic magnitudes of RS Ophiuchi (Shapley).

For many years L. C. Peltier has perseveringly followed this star. His observations since 1921, published in these reports, indicate that the star has remained close to 11.^{m}1 except for rare variations of about half a magnitude each side of this value until last August when he announced[4] that the star had been 6.^{m}4 on August 15. Thereupon Dr. J. A. Pearce suggested that the writer follow the star with his 4-in. refractor and kindly helped in locating it.

A map[5] of the region surrounding the star was prepared from the Henry Draper Catalogue and estimates made of the magnitude of the nova on every suitable night using pairs of comparison stars selected from this map. Power used, ×30.

[3]Popular Astronomy.

[4]Harvard Announcement Card No. 272, Aug. 16.

[5]Journal R.A.S.C. XXVII, p. 338.

As the star was deep red in colour when first observed and personal colour correction was unknown, all immediately available observations were collected and are plotted along with the writer's observations in Fig. 2, which shows the resulting preliminary light curve.

Mr. Peltier kindly made available for this purpose his recent observations of the star and grateful acknowledgement is made.

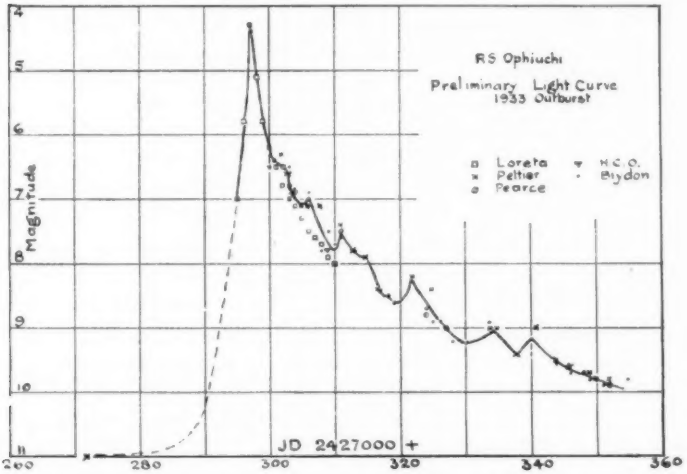

Fig. 2. Preliminary light curve of RS Ophiuchi, 1933 outburst.

Sig. Eppe Loreta, of Bologna, Italy, appears to have been lucky enough to have caught the star at or near the actual maximum. A free translation of his announcement,[6] dated August 30, reads:

"On the evenings of the 9th and 10th of August I was observing Y Ophiuchi and did not notice anything unusual. On the evening of the 11th I observed with surprise RS to be $5.^m8$. On the 12th it had increased 1.5 magnitudes to about $4.^m3$. The following days it diminished progressively with decreasing rapidity."

During the recent outburst then, RS Ophiuchi appears to have increased from magnitude 11 to $4.^m3$, so that it was some 500 times

[6] A.N., No. 5975, Vol. 249, p. 403.

brighter than a few days previously. Its brightness at this maximum was about 23 times greater than in 1898.

The occurrence of a second outburst of a nova is rare. Another notable instance is the star T Pyxidis, normally of the 15th magnitude, which has risen to maxima greater than magnitude 8 three times, in 1890, 1902 and 1920.[7] Examination of the present spectra of old novae may indicate some that should be watched for a similar recurrence. P Cygni may yet be an instance.

The term 'peculiar irregular variables' seems to describe such stars as RS Ophiuchi and T Pyxidis better than 'novæ'.

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[7]Russell, Dugan and Stewart, Vol. 2, p. 779.

NOTE ON THE OBSERVATION OF THE TOTAL ECLIPSE OF THE SUN ON AUGUST 31, 1932[1]

By A. de La Baume Pluvinel and D. Barbier

We made observations of the last total eclipse of the sun at Louiseville in Canada. At this point, situated midway between Quebec and Montreal, the duration of totality was 100 seconds. On the day of the eclipse the sky was clear during the morning but it started to cloud up a little before the eclipse was due and the first contact was observed through clouds. At the time of totality the sky was still cloudy but by good fortune the sun was situated in a clear spot so that the total phase was observed under good conditions. Shortly afterwards the sky was completely overcast.

Most of the instruments used were mounted on the same equatorial axis. The chief observations which we were able to make were the following:

1. A coronograph, the optical parts of which consisted of a photographic objective of 10-cm. diameter and a diverging lens, gave an image of the sun 38 mm. in diameter. Two Lumière Lumichrome plates were exposed during totality. The times of exposure were 15 and 75 seconds. The photographs show short aigrettes sharply defined at the poles of the sun and in the sunspot zones the coronal streamers more or less extended. One of these on the northeast limb of the sun is visible to a distance of 40′ from the edge of the solar disk. Two others, on the west limb, are large but do not extend so far. This form of the corona, called that of minimum solar activity, is frequently observed several years before and after sunspot minimum. We may recall that the next minimum is expected in 1934.

The density at different points on the coronal plates was measured by means of a density meter developed by M. Jules

[1]Translated from *Comptes Rendus*, vol. 196, p. 1345, 1933, by P. M. M.

Baillaud. These measures were made so as to find points on the plates where the density equalled a certain given value. It was now possible to draw six curves through these points of equal density, these curves of necessity being isophotes. These densities were converted to intensities through a knowledge of the characteristic curve of darkening of the photographic plate. Taking the sky background as unit intensity, the six isophotes had intensities of 2.08, 2.87, 4.56, 11.4, 28.07, 72.3.

2. Three slit spectrographs were used to study the spectrum of the solar corona. The fastest spectrograph, a one-prism instrument, gave the best results. A single exposure was made for the duration of totality. The slit was set along the diameter of the sun perpendicular to the solar axis. Each edge of the sun gave a continuous spectrum with superposed emission lines. The distribution of intensity in the continuous spectrum seemed to be the same as in the solar spectrum. The continuous spectrum extended from Hα to Hη, the length between these two lines being 60 mm.

At the solar limbs two lines appear whose origin is essentially coronal. These are the green line at λ5303 and the red line at λ6374. The first is visible to a distance of 5′ from the edge of the sun, the second to a distance of 3′. They extend much further from the solar limb than the continuous spectrum. The green line is more intense than the red line and if the former were given intensity 10, the latter would be estimated of intensity 7.

Besides the essentially coronal lines, a large number of chromospheric lines are present. These latter are much more numerous at the east limb than at the west which is without doubt owing to the fact that a deeper layer of the corona was uncovered at the east limb, that is at the beginning of totality, than at the end. In the spectrum of the east limb 25 chromospheric lines can be counted while in that of the west limb only the lines of hydrogen and the D_3 lines can be identified.

The spectrum of each limb of the sun has been examined with a registering microphotometer by M. D. Chalonge. This showed evidence of chromospheric lines which were hidden by the continuous spectrum and could not be seen by direct means. Another fact should be noted. At the east limb, where the lines are more numerous, all the lines are bright and constitute an emission

spectrum, but at the other limb a great number of the lines are reversed and form an absorption spectrum. This fact is particularly evident between the wavelengths λ4900 and λ5300. One can in addition, by means of the microphotometer, distinguish the presence of the telluric water vapour line at λ6280.

3. Two objective prism spectrographs were used. One of these had optical parts of iceland spar and quartz and gave a spectrum extending from λ3100 to λ5900. The shutter having been closed a little late after third[2] contact a thin solar crescent gave the Fraunhofer spectrum along a central band while on either side of this were the monochromatic arcs produced by the light of the lower part of the chromosphere, in other words the flash spectrum. None of these chromospheric arcs can be attributed to the corona.

4. We thought it would be interesting to measure the intensity of the light of the whole corona as a contribution to the study of the way this changes from one eclipse to the other. Since it is difficult to make visual photometric measures during the brief duration of totality we used photographic photometers so that it was the actinic light of the corona which we measured.

The first photometer consisted of a camera in which the lens had been replaced by a diaphragm with a circular opening. The diameter of this opening was calculated so that all points of a small section of the photographic plate were directly lighted by a circular portion of the sky, 1.5 degrees in diameter and centered about the corona. To take account of the general light of the sky which is superposed on the light of the corona, several sections of the plate neighbouring to that which received the light of the corona, were exposed to parts of the sky around the corona. Analogous experiments on the full moon were made last December under similar conditions. The density of the different sections of the plates was measured and after having included in the result all the corrections deemed necessary we found for the total light of the solar corona a value of 0.80, the light of the full moon being taken as unity. This result is in good agreement with the determinations made by various observers during preceding eclipses.

5. We used another instrument to measure the total light of

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[2]This was *second* in the original—Tr.

the corona. Since Jupiter was quite near the sun during totality we thought it would be interesting to compare the luminosity of the corona to that of the planet whose magnitude is known. We thus become independent of a terrestial source of comparison and of the absorption of light by our atmosphere.

The instrument used was a photographic photometer with a ring ocular based on the principle given by M. Ch. Fabry. During totality different regions of the photographic plate were exposed to the light of the corona of the sky and of Jupiter respectively. Various methods were employed to reduce the intensity of the corona and of the sky background. In spite of the precautions taken, however, the difference between the darkening of the plate by the sky alone and by the sky plus Jupiter was too slight to enable the determination of the luminosity of the corona as a function of that of the planet to be made with any degree of certainty. Nevertheless, taking the magnitude of Jupiter as -1.3 we have found for the magnitude of the corona a value of -10.9. It is interesting to compare this number with the stellar magnitude of the full moon, -12.5.

The determination which we have made of the light of a square degree of sky in terms of the total light of the corona is much more accurate. We found for this the value 0.0156. We consider, for various reasons which cannot be gone into here, that the value of this ratio indicates that the sky is lighted during totality by the light of the sun doubly diffused.

6. Among our instruments we had a coronograph constructed from the plans of M. Lyot with which we proposed to photograph the solar corona when the sun was only partially eclipsed. This part of the programme could not be carried out because of clouds but a plate was exposed during the whole duration of totality. The red screen of the Lyot coronograph naturally reduced the extent of the corona on the plate, it being a ring 10′ in width. We might add that some minutes after totality, by observing visually with the instrument, we were able to see the lunar disk separate itself from the solar corona exterior to the sun.

W. H. PICKERING AND THE MARKINGS ON MARS

By the Editor

WITH the publication in the February issue of the paper on Mars by Mr. H. Boyd Brydon and the reply to it in the September issue by M. Antoniadi the discussion was declared closed. Both of these writers made reference to Professor W. H. Pickering and the latter has sent a communication to the present writer stating that what he had written was incorrectly quoted and hence his views were not fairly stated. The Editor is unable to print Professor Pickering's communication but he thinks a true statement of the facts should be given.

As is well known Professor Pickering has had many years' experience in observing Mars and has published much material on the planet. Among his writings is a series of "Reports" which were printed in *Popular Astronomy*, No. 1 appearing in January 1914. Report No. 35 was in the issue for May, 1926, and dealt with the opposition of the planet in 1924. In the course of this paper its author discussed the results obtained with the great telescopes at Greenwich, Meudon, Yerkes and Mount Wilson; and in a table he states which of four "canals" which he names could be seen by each instrument.

With the above introduction let us quote what Mr. Brydon says in his article (page 68):

> Further as W. H. Pickering remarks (Report on Mars No. 35, *Pop. Ast.* 1926) Meudon "lies in the great anti-cyclone belt of our planet. Within that belt seeing never is and never can be comparable with what is usually found in more southern localities." Under such conditions it is not surprising that fine detail is not seen at Meudon.

It is to be noted that the last sentence is not quoted from Professor Pickering.

Then in M. Antoniadi's paper (p. 286) is the following:

> The quotation from Mr. W. H. Pickering, that Meudon is situated in the anti-cyclone belt, never yielding fine definition is unfortunate, as the same Mr. Pickering wrote that in 1924, during the "test of giant telescopes . . . . Meudon came off best, and detected the most fine detail."

In order to bring order out of the confusion which has arisen it will suffice to quote just what Professor Pickering did say. In his paper he gives a table, the last column of which states the number of the four test canals referred to above which could be seen in the different telescopes. He then remarks (p. 303):

> In this test of giant telescopes it will be seen by this column that Meudon came off the best, and detected the most fine detail. It also incidentally scored in the total number of confirmed lakes that were seen with it. In this matter in fact it nearly equalled the 36-inch Lick telescope which showed 13, but it was hardly in the same class with the Lick in the matter of fine detail, as indicated by the number of canals recorded.

Also in the last paragraph (p. 306) he says:

> Although not applying so directly to Mount Wilson, another obvious handicap of the remaining three large telescopes just discussed, the Greenwich, Meudon, and especially the Yerkes, is that they lie in the great anticyclone belt of our planet. Within that belt the seeing never is, and never can be, at all comparable to what is usually found in certain more southern localities. In these latter the best planetary observations always have been, and always will be made, and it is of no use for other stations, no matter what their equipment, to try to compete with them.

SPECTRA OF THE NIGHT SKY, THE ZODIACAL LIGHT, THE AURORA, AND THE COSMIC RADIATIONS OF THE SKY*

By V. M. SLIPHER

ALL who have thoughtfully looked upon the clear moonless night-sky are aware that it is not quite dark but that, besides the stars, planets, and Milky Way, it is everywhere faintly luminous.

Believing valuable information would be gained regarding the nature and origin of this weak, diffuse sky-light by spectrographic investigation, I made, in 1915, at the Lowell Observatory, the first attempt to photograph its spectrum. Since then I have continued the study as opportunity has afforded, and with rather remarkable results.

The extreme faintness of this diffuse light has been the real obstacle to the study of its spectrum. To photograph it, even with the speediest plates and long exposures, requires special spectrographs of the greatest possible light-power. During the progress of the work it has been possible from time to time to increase much the efficiency of the instruments. Finally, a couple of years ago, I was able to design a new type of spectrograph which has been especially efficient because it is able to record simultaneously as many as five spectra, side by side, of the light of as many different portions of the sky. During the past year, two instruments of this type have gathered data rapidly and have greatly advanced the study.

It has been observed at Flagstaff since 1915 that the chief auroral line is always present in all parts of the sky, that it is more intense in the sky nearest the sun, that it is weakest in the zenith, and that it varies somewhat in intensity; however, it is not accompanied during the dark of the night by the negative nitrogen-bands, which are so typical of auroral-display light, and yet the observations showed it to have the same wave-length and same appearance in the sky as in the auroral displays. It was found that the wave-length of this line was fully six units greater than the

*From *Transactions of the American Geophysical Union*, 1933.

long-accepted value, and this large correction stimulated renewed study of this interesting radiation.

Then next, long exposures—100 hours or more—revealed the presence of a number of other features in the sky-light spectrum. Some of these were evidently emissions; others could be emissions or their appearance might be due to adjacent absorptions. In time it became evident that they were for the most part emissions and also that they were not of the auroral-display series. They were spread throughout the blue and violet and one interesting one also in the yellow near 5900. I first thought these strange features of the sky-spectrum might be due to very distant faint stars whose light and spectra might differ from the nearer stars. But this view could not be substantiated for there was no blend of light of known types of stars that would yield a spectrum having the features that the sky-spectrum showed. And it became more and more patent that these new spectral features belong to a strange type of spectrum that is peculiar to the diffuse light of the sky. These emissions I shall refer to as the cosmic radiations of the night sky.

During the brilliant aurora of May 14, 1921, I photographed a bright red line or band near λ6315, and in long-exposed spectra of the night sky I found the new yellow line near λ5900 was repeatedly recorded. Both these radiations, one auroral and the other sky, were seen to be fairly intense lines. It thus seemed very desirable to explore the red end of the sky-spectrum. The photographic obstacles I discounted by the thought that any emissions there would stand out clearer because of the low scattering-power of our air in the red. The extension of the study into the red promised to give additional information on the aurora and more still on the strange or cosmic radiations of the sky-spectrum. These efforts in the red were abundantly rewarded for new radiations were found there in surprising strength and numbers. Repeated plates continue to show these radiations and leave little doubt they are of a permanent nature, resembling the chief auroral line in the yellow λ5577. In order to get the spectrum, low dispersion is needed and this allows only approximate values of the wave-lengths. After a time, it was seen that these new radiations varied among themselves and in comparison with the yellow auroral line which years earlier had itself been found to vary.

At about the same time this study of the red spectrum was taken up, I found weak impressions of the typical auroral nitrogen-bands could be photographed in the morning and evening skies, if brief exposures were made at the critical moment when the first, or last, traces of sunlight touch the high atmosphere. These twilight auroral bands are commonly present and more intense in the sky toward the sun. It may be repeated here that these auroral nitrogen-bands are never present during the dark of the night, except when an aurora is present.

Meanwhile I have also secured spectra of the zodiacal light and wish to digress a bit from the sky subject to touch upon this and the related phenomenon, the "Gegenschein". Recently new plates of these have been got with the multiple-image spectrograph. In this way it has been possible to photograph the spectra of the zodiacal light and Gegenschein under very favourable conditions, in that the spectra of regions of the sky removed from these subjects could be got simultaneously and brought alongside the studied spectra, making reliable comparisons possible. These new plates of the zodiacal light show a fairly strong background-spectrum of sunlight. Superposed upon this are, of course, the brightest of the night-sky cosmic radiations and also weak impressions of the negative nitrogen-bands typical of the spectra of aurorae. It is difficult to decide just how much of the strength of these nitrogen-bands is due to the zodiacal light since the twilight usually has these same bands. Further work using spectra made later at night and farther from the horizon may clear up this question. I am not able to decide from my Gegenschein spectra that the negative nitrogen-bands are present, but if so, they must be very faint. There also appears some doubt whether the continuous spectrum of the Gegenschein is slightly intensified by sunlight. Of course, the cosmic radiations of the night sky are superposed upon these Gegenschein spectra and they make it difficult to decide whether other very faint Gegenschein bands are also present.

Returning to the sky again, recently it has been possible to photograph the red sky-radiations with twilight-prism dispersion, and to improve the wave-lengths of some of them. It seems the radiation in the yellow falls very near the position of the sodium lines, whatever that may mean. The radiation near wave-length

λ6315 (by earlier measures) is now clearly resolved into three lines. The middle, and much the strongest, is, by measurement, very close to wave-length λ6300, and the second strongest near wave-length λ6360, its weakness making it less accurately measurable. These two lines are by these measures well within expected agreement with the two forbidden lines of oxygen, wave-length λ6300 and wave-length λ6363, intensities 4 and 1, which are related to the yellow auroral line of forbidden oxygen. In wave-length and in relative intensities the agreement seems quite satisfactory. Those red lines of greater wave-length are not yet well enough resolved and measured for identification.

Again, with the use of plates specially prepared and sensitive for the deep infra-red, I have recently discovered a new group of most remarkable sky-radiations. These are much more intense than those in the orange and red. Attempts to secure them with the 2-prism instruments have not yet met with success, and thus it is not now possible to give wave-length spectra of them of useful accuracy, nor is it possible to distinguish between lines and bands. There are seven or more of these, from wave-length 7200 to wave-length 8800, the strongest of these being near λ7400, λ7500, λ8250, λ8400, and λ8600. Of these the second and those at λ8250 and λ8600 are the most intense. While we must wait for more and better plates for useful wave-lengths and identifications, it tempts one to venture to point to the strong oxygen-lines in this region as likely to be involved in these brilliant new sky-radiations.

The remaining light of the sky, after deducting that coming from the stars and from the various types of auroral light, leaves an emission-spectrum of a great number of what we may call cosmic radiations as recorded in this study at the Lowell Observatory. These are distributed throughout the spectrum from the ultra-violet to the deep infra-red. These together must comprise the major fraction of the diffuse light of the night sky. This is especially true of the red and infra-red light, for there the scattered starlight is relatively very weak. Thus the early assumption that this faint diffuse night sky-light was due to stars must be considerably modified.

It has not been an easy matter to decide where the light giving these cosmic sky-radiations has its origin. With the new spectro-

graph, the spectra recorded of the four regions in the north, east, south, and west sky a little above the horizon and another in the zenith, for comparison, show that these unidentified radiations are relatively stronger in the visual end of the spectrum for low regions of sky whereas for the zenith the violet of the spectrum is fully as strong as are the spectra of the low-altitude regions. Although we are doubtless dealing to some extent with general atmospheric absorption, which is most for the shorter wave-lengths, there is in my judgment another matter involved. This is the apparent strengthening of the longer sky-radiations with the increased air-path. It appears that this has more to do with the increased strength of the sky-radiations toward the longer wave-lengths than mere lack of absorptions appears to strengthen the shorter wave-lengths. In brief, this appears to make a fairly strong case that these unidentified cosmic radiations, for the most part, have their origins in the earth's atmosphere. And we are led to believe the origin is some distance above the earth's surface and that the layer of upper air involved may have quite appreciable thickness.

Tests have been made for altitude—effects at altitudes above and below that of the Lowell Observatory at Flagstaff. Its altitude is 7250 feet above the sea and tests were had at 10,500 and 3,000. The indications were that the sky-radiations were relatively to the spectrum-background more intense at the highest elevation. But the conditions were not the best, especially for the tests at the lowest station, and it is desirable that these be repeated before considering that matter settled.

An attempt was also made in August, 1932, to test the sky for these radiations during the total phase of the solar eclipse, but the results are hardly conclusive as the plates are too fully exposed to be able to show the type of radiations sought.

Further study of these radiations, especially those in the red and infra-red, where they are more intense relative to the blue, can not fail of valuable results, and the work is now in progress. While we can not in the time alloted us here follow this subject further, it is evident, I think, that we see our atmosphere taking on very remarkable optical rôles.

Lowell Observatory,
Flagstaff, Arizona.

SOME RESULTS OF FURTHER STUDIES IN THE CORRELATION OF COSMIC PHENOMENA WITH RADIO INTENSITIES AS MEASURED AT THE PERKINS OBSERVATORY*

By HARLAN T. STETSON

RESEARCHES in the investigation of the correlation of solar activity with radio reception have continued at the Perkins Observatory in the measurements of field-intensities of WBBM, Chicago, during the night hours from 9.00 p.m. to 2.00 a.m., Eastern Standard Time. Following the method of procedure outlined to the American Geophysical Union in 1932, the measurements have been corrected for the angle of depression of the sun below the horizon after the correction-curve as was determined by Mr. Cobb.

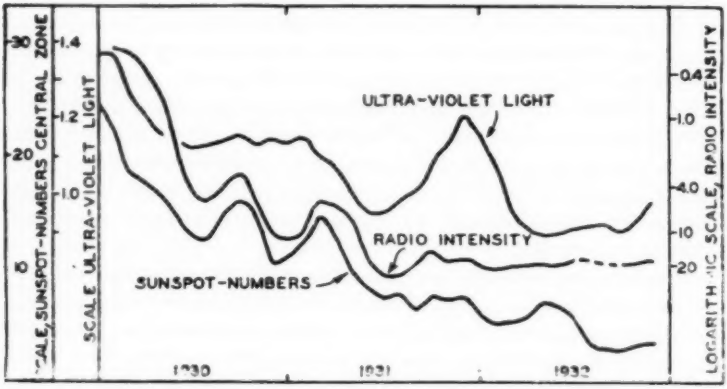

Fig. 1. Comparison radio intensities, sunspot-numbers, and ultra-violet light.

Comparisons of radio intensities expressed logarithmically with the sunspot-numbers (see Fig. 1) confined to the central zones show a somewhat closer correspondence than when compared with

*From *Transactions of the American Geophysical Union*, 1933.

sunspot-numbers for the whole disc, adding further evidence for an apparent direct sunspot-effect on the altitude of the Kennelly-Heaviside layer. The fact that the curve of radio intensities compares more closely with the sunspot-curve than with the curve of ultra-violet light, as determined from Pettit's measures at Mount Wilson, suggests that the increased ionization of the upper layers is effected by other considerations than the integrated ultra-violet light of the whole solar disc.

The investigation of a lunar effect upon radio from Perkins Observatory data has been continued. Josef Johnson has correlated the actual luni-tidal force at latitude 40° with the intensities of radio reception and finds evidence for points of inflection in the intensity-curve corresponding to critical values in the tidal force which presumably suggests critical layer-heights for optimum reception.

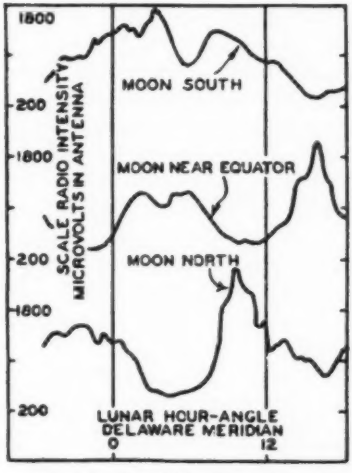

Fig. 2. WBBM radio intensity at Delaware and lunar hour-angle.

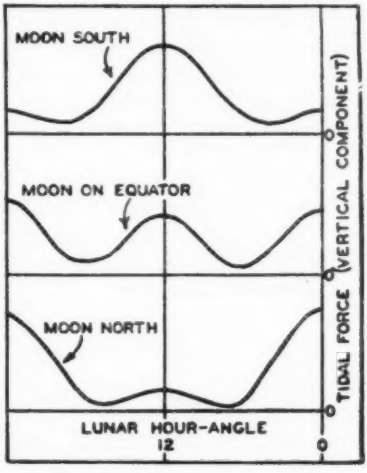

Fig. 3. Theoretical semi-diurnal tides, latitude 40°.

Further analysis of the data subsequently obtained during more than two years has brought to light not only an apparent variation of field-intensities with the lunar hour-angle, but also

with the lunar declination. Curves of Figure 2 show the values of field-intensities at lunar hour-angles 0 to 24, and for three cases, namely, (1) moon south at declinations $-12°$ to $-28°$, (2) moon at the equator at declinations between $-12°$ and $+12°$, and (3) moon north of the equator at declinations $+12°$ to $+28°$. The fact that the two curves representing north and south declinations are inverted in phase is highly suggestive of tidal phenomena in the Kennelly-Heaviside layer. The curve representing field-intensities with the moon near the equator suggests semi-diurnal tides. A comparison of these curves with the curve of equilibrium-tides for latitude 40° (see Fig. 3) may be suggestive in arriving at some sort of explanation of a lunar effect upon the Kennelly-Heaviside layer. The fact that the tides at extreme declinations are diurnal, and that the semi-diurnal maxima occur for the case where the moon is near the equator, does not appear inconsistent with variations dependent upon latitude and the production of tides in an atmospheric ocean. It is difficult to explain the large variations here found on any simple gravitational tides in the atmosphere. A theory involving resonance may, however, be sufficiently elastic to offer some basis for explanation. Whether or not other sources of gravitational attraction enter into the problem involves further investigation.

REV. D. B. MARSH

Daniel Brand Marsh died in Hamilton on September 22, aged 74 years. He was born on a farm near Walter's Falls, not far from Meaford, Ont. He attributed to his mother his early interest in astronomy which was quickened by first lessons given him with the aid of a small telescope. His natural inclination towards mechanics was shown by his construction at the age of fifteen years of a small steam engine, made from material around his home. His finer mechanical gifts were further developed by apprenticeship to a watch maker. This served him well in later years when he undertook to construct a number of telescopes. After attending Knox College, which is affiliated with the University of Toronto, he entered the ministry of the Presbyterian Church, a connection he maintained to the time of his death. Whilst a busy minister he purchased a lathe and its necessary accessories and set it up in the basement of his home. Here he spent his spare hours constructing various mechanical devices, among them being a stethoscope, an audiphone and a cylinder phonograph after the pattern of Edison's. In 1901 he became a member of the Royal Astronomical Society of Canada and then during his leisure turned his attention to constructing refracting telescopes. A number of these were made with equatorial mounting and driven by clock work, Brashear or Watson-Conrady object glasses being employed while the mechanical parts were the work of his own hands. A number of these instruments were placed throughout Canada and have been admired for their excellence of workmanship.

Dr. Marsh was mainly responsible for the formation of Centres of The Royal Astronomical Society of Canada at Peterboro, Guelph and Hamilton. His ministerial work called him to Bermuda for the period 1920 to 1925, where his untiring energy would not allow him to neglect astronomical matters. While there he not only interested the public in astronomy but also assisted navigators by giving time and correcting their instruments. In 1925 he was the leader of a party sent by the Bermuda Government to New Haven, Conn., to view and photograph the eclipse of the sun.

Before returning to Canada he visited Trinidad and British Guiana and while there contracted malaria from which he apparently never entirely recovered. He presented a telescope to Captain Bernier who had it with him during his arctic voyages. One of his telescopes was presented to the Presbyterian College at Indore, India, where it is still in use. He was elected a Fellow of the Royal Astronomical Society in 1904.

He was a member of the Astronomical Society of France, of Belgium and of Mexico. In 1905 he was a member of the Canadian Government eclipse party sent to Labrador, and in August of last year headed the Hamilton party at Acton Vale, Quebec, where he succeeded in securing several excellent photographs of the eclipse. In his photographic outfit was included a concave lens inserted inside the focus of the telescope, somewhat similar to that known as a Barlow lens, to amplify the resulting image. A few weeks before his death Dr. Marsh was the recipient of a grant of $1,000 from the Dominion Government in recognition of his long service in the interests of astronomy in Canada. Dr. Marsh was given degrees in philosophy and science through a post-graduate course at Chicago.

There are left in the immediate family his widow, Cora Burling Marsh, who has always assisted him in his work; two daughters, Mrs. Mary Marsh Mesnard, of Hamburg, N.Y., and Dr. Ina A. Marsh, of the Buffalo City Hospital; and a son, John A Marsh, of Hamilton, Past President of the Hamilton Centre, R.A.S.C., who was associated closely with his father in the latter years of his life. An older son, Lieut. James W. Marsh, who held an important position as mechanical expert with the C.N.R., was killed in action at Passchendale in 1917.

THE CONSTITUTION OF THE STARS*

By Henry Norris Russell

TO number and name the stars is easy enough—or would be so if there were not so many of them; but to determine their real nature, and discover how and why they shine, is a task which, though well begun, is not more than half done.

(1) The Properties of the Stars

We have many ways of gaining information about the outside of a star. First and foremost, by collecting its light with a telescope and feeding it into a spectroscope, we learn that the stars, like the sun, are self-luminous incandescent bodies surrounded by atmospheres which contain the familiar chemical elements in a gaseous state. All the elements which are most abundant on earth have been found in the stars, and many of the rare ones—more and more as more powerful instruments can be applied—and few unidentified spectral lines remain, so that we can be sure that the stars are essentially similar in composition to our own world. No conclusion of science is more significant than this. The poet Stedman has expressed its meaning better in verse than any technical prose could render it.

> White orbs like angels pass
> Before the triple glass
> That men may scan the record of each flame,—
> Of spectral line and line
> The legendry divine
> Finding their mould the same, and aye the same,
> The atoms that we knew before
> Of which ourselves are made,—dust, and no more.

The materials of nature, and her laws, are the same everywhere. Upon this foundation we build.

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*First Maiben Lecture before the American Association for the Advancement of Science, given at Atlantic City on December 30, 1932. Reprinted from *Science*.

Applying these laws to our observations of the stars' light, we may calculate the temperatures of their surfaces—for the hotter an incandescent body is the more blue light it emits in proportion to red. Comparison with laboratory sources shows that the stars begin about where these leave off—very few having surface temperatures less than 3,000° and the great majority ranging from three up to fifteen or twenty thousand degrees (on the Centigrade scale). Some exceptional bodies may reach 50,000°. These conclusions are checked by other methods and entitled to confidence. At even the lowest of these temperatures, all but the most refractory chemical compounds are decomposed into their elements—which immensely simplifies the physical situation—and, higher up in the scale, the atoms themselves lose one or more of their outer electrons, becoming ionized and giving new and different spectra. The conspicuous differences between the spectra of the hotter and cooler stars originate from changes of this sort, combined with other and equally well-understood effects of temperature. When allowance is made for these, it is found that, despite the apparent diversity, the stars, or, at least their atmospheres, are remarkably similar in composition. The relative proportions of atoms of different kinds are very similar to those which are found in the earth's crust, with one important exception. Hydrogen, which forms but a small proportion of the earth's mass, is more abundant in the sun and stars than anything else. Helium is also abundant. It is reasonable, by the way, to suppose that these light gases escaped from our planet (which has not enough gravitative power to hold them) shortly after its birth as an independent body.

Finally, from the temperature and degree of ionization in stellar atmospheres, it follows that the pressure must be very low—something like a thousandth part of that of the air which surrounds us at sea-level. The pressures are different, of course, in different stars, but are always small.

Why we do not see down into regions of greater density and pressure was once puzzling; but it is now known that an ionized atmosphere, full of free electrons and charged atoms, will scatter light like a thin fog. This prevents us from seeing down deeper. The calculated temperature represents an average for the partly foggy layers toward the bottom, from which most of the observable light comes.

All this information could be obtained by spectroscopic means, if we knew nothing about the distances of the stars. Measurements of distance, which have now been made in various ways, for thousands of them, give us new data. The real brightness, or luminosity, shows a remarkably wide range. Our sun is not far from the middle of this range, and forms a convenient standard. Stars 100 times as bright are common. Many are known to be more than 1,000 times as bright, and a few give more than 10,000 times the sun's light. On the fainter side stars down to 1/100 and even 1/1,000 of the sun's brightness are common and a few are known which give but 1/10,000 of its light. Only the very nearest of these are visible to us, even with good-sized telescopes, so that there is not much chance of picking up the still fainter ones which probably exist. Very bright stars, on the contrary, can be seen at enormous distances, and our failure to find them indicates that very few such objects exist. There are, of course, various ways of measuring luminosity—with the eye, which is sensitive mainly to yellow and green light, with photographs, which work in the violet, and with heat-measuring apparatus, which is sensitive to all radiations alike. The corrections necessary to reduce measures on the other scales to the last (which is obviously the best for theoretical studies) can be calculated when the star's temperature is known.

If we know the luminosity and temperature of a star, we can at once calculate its size—its actual diameter in miles. Once more our results can be checked, by Michelson's beautiful interferometer method, and by various others, and it is found that the unavoidable assumption that the hazy indefinite lower atmosphere behaves like a hot solid surface, of standard properties, at a suitable average temperature, leads to reliable results. The stars differ less in diameter than in brightness. The general run of stars have diameters ranging from three or four million miles to about half a million (comparable with the sun's 866,000). Some are much larger, from ten million miles to five hundred million in extreme cases, while a few are abnormally small, from 50,000 miles to 10,000 or even less.

Direct information about the interior of a star can be gained in only one way—by means of gravitation. Here, and here alone, the inner portions exert their full action, quite independent of their

envelopment by great masses of matter. At ordinary interstellar distances, the mutual gravitation is quite negligible; but, fortunately there are numerous binary pairs in orbital motion controlled by gravitation. For many such systems we can derive reliable values of the masses. These differ far less widely than the sizes or luminosities. The greatest mass so far measured is 113 times that of the sun, the least 0.18—a ratio of 700—as against 50,000 for the diameters, and more than 100,000,000 for the luminosities. Why this should be true is a problem for the theorist, which, as we shall see, has been successfully answered.

In density, the stars differ amazingly. Some stars have more than 100,000,000 times the sun's volume, and probably less than 100 times the sun's mass. The density of such a star is of the order of a thousandth part that of ordinary air. Those of smallest diameter are massive, and some of them have densities as high as 50,000 times that of water—almost a ton per cubic inch! How such tenuous bodies as the first can hold together and shine and how any material substances can be as dense as the second are other problems which have been satisfactorily solved.

These calculations tell us only the average density of the material inside a star. How much denser it is in some parts than others can be determined only in a few favourable instances—double stars whose components revolve in an eccentric orbit and, being separated by but a few diameters, are pulled out into ellipsoidal shapes by their mutual attraction. In this case the periastron (or point of closest approach) moves slowly forward at a rate which depends not only on the sizes and masses of the stars, but on the extent to which the density at the centre exceeds the average. Only one system (Y Cygni) has so far been carefully studied. In this it appears that the concentration of density toward the centre is large.

Barring this rare good fortune, all that we can find out observationally about a single star, in addition to its chemical (or atomic) composition, may be expressed by three numbers defining its mass, its radius and its luminosity. From these the density and the surface temperature may immediately be computed.

(2) Relations between these Properties

These properties of the stars are not distributed at random, but are related among themselves in very striking ways. The simplest

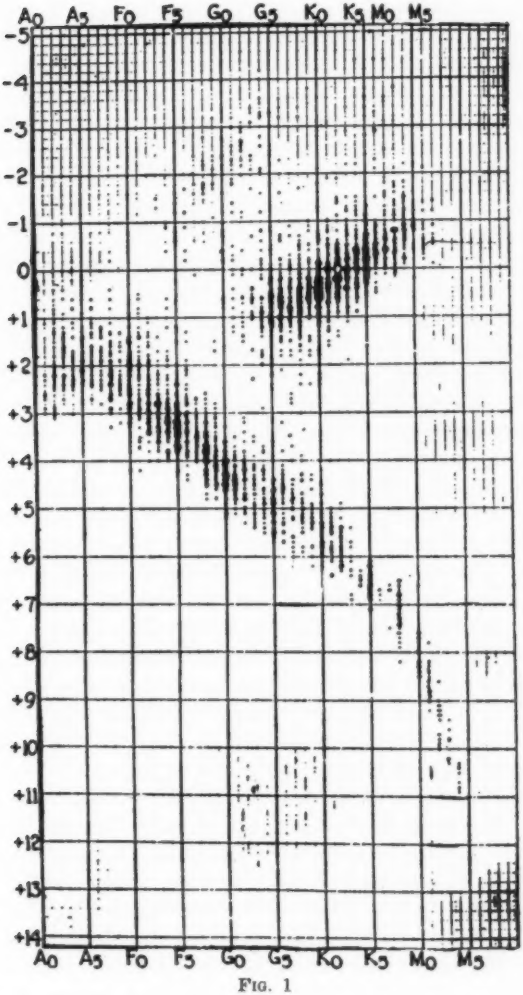
A0 A5 F0 F5 G0 G5 K0 K5 M0 M5
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
+8
+9
+10
+11
+12
+13
+14
A0 A5 F0 F5 G0 G5 K0 K5 M0 M5

FIG. 1

and perhaps the most important of these correlations is that between mass and luminosity, discovered by Eddington. Stars of large mass are always bright, and stars of small mass faint. A star of the sun's mass has nearly the sun's brightness; one of 4 times the sun's mass gives about 80 times as much radiation, and one of 16 times the mass 1,600 times as much while one of ¼ the sun's mass radiates only about 1/200 as much heat.

Strangely enough, the size of a star seems to have very little influence on this relation. Red stars, fifty times the sun's diameter, and white stars only two or three times as big as the sun, if of the same mass, have nearly the same luminosity. Indeed, if a curve is plotted, representing the relation just indicated, with points corresponding to the data for individual stars, the deviation of the latter from the smooth curve averages hardly greater than the effects of the outstanding error of observation. There is but one exception. The stars of very small diameter, and very great density, are much fainter than others of equal mass—from 1/10 to 1/100 as luminous.

The luminosity and surface temperature (or the closely related spectral type) of a star are also correlated, but in a more complicated way, best illustrated by a diagram. Fig. 1, prepared from observations of about 4,000 stars by Adams and his colleagues at Mount Wilson, shows the brightness (on the familiar scale of stellar magnitude) plotted against the spectral type—each dot representing one star. The points are very far from scattered at random. The majority of them congregate in a narrow band, crossing the diagram downward and to the right. Along this line, called the *main sequence*, we pass from bright, hot and massive stars, at the top, to faint, cool bodies of small mass at the bottom.

The hottest stars of all are not shown in the figure. They extend the sequence upward and to the left. The sun belongs to this sequence, and is a fairly typical member. Though so different in brightness and in mass, these stars are fairly similar in size. A member near the top might be of 10 times the sun's mass, 4½ times its diameter, 1/10 its density, 800 times its luminosity and 2½ times its surface temperature. One near the bottom might have about ¼ the sun's mass, 3/10 its diameter, 9 times its density, 1/180 of its luminosity and half its surface temperature. There is

an unbroken series of stars all the way between these types, and even beyond them, and the whole obviously forms a natural family. The great range in brightness within it arises mainly because the radiation from equal areas varies as the fourth power of the surface temperature.

A second sequence of stars is represented on the upper right-hand part of the figure. Hertzsprung's name of "giant stars" is very appropriate, for they are of gigantic size. Capella, which belongs at the lower left of this sequence, has in round numbers 4 times the sun's mass, 125 times its brightness, 14 times its diameter 90 per cent. of its surface temperature and 1/700 of its density. A red giant at the upper end would have some 10 times the sun's mass, 1,500 times its luminosity, 150 times its diameter, ½ its surface temperature and less than 1/200,000 of its density. Here is evidently another natural family of stars. According to the data represented on our diagram, they are rather sharply separated from the main sequence, but Strömberg's calculations, based on other data, indicate that the gap is partially filled up.

A number of very bright stars are represented by scattered dots near the top of the diagram. These are the "super-giants" of which examples are found in almost every class of spectrum. A fourth important class of stars, the white dwarfs, would be represented by points in the lower left-hand corner. They are far fainter than those main-sequence stars of the same temperature, and so must be much smaller—indeed, their computed diameters range from 30,000 to 8,000 miles, no larger than the planets. Their masses, which can fortunately be determined in a few critical cases, are considerably larger than those of main sequence stars of the same luminosity, and their densities come out extraordinarily great, up to a ton per cubic inch, as was already mentioned. Few of these stars are known; but they are so faint that only those which lie very near the Sun (as stars go) can be adequately observed. There must be thousands of others, visible in great telescopes, but lost among the countless swarms of faint stars. This is typical of the effects of observational selection which meet the student of the stars wherever he turns, and demand eternal vigilance, lest they lead him astray.

(3) The Problem to be Solved

The great task of theoretical astrophysics is to interpret these properties of the stars—individual and collective—by means of the general physical properties of the matter of which they are composed. Here we are greatly aided by the high temperatures of the stars. Chemical compounds are decomposed; hence we have to deal only with the properties of atoms, and of course of electrons and protons, and of light-quanta. Hence, the more we know about atoms, the more we can find out about the stars. The minutest things in nature give us the key to unlock the secrets of the greatest.

We must ask the physicist to answer three main questions:

(1) What is the *equation of state* inside the star—the relation connecting the pressure with the density and temperature?

(2) What is the *opacity of the material* which regulates the flow of heat from the intensely hot interior to the surface, and supplies the loss by radiation into space?

(3) By what processes, and according to what laws, is the *internal supply of heat* kept up, so that the star does not gradually cool down and go out?

We have now a satisfactory answer to the first question, and a fairly good one to the second; but only a beginning has been made with the third, though there is hope that we may know more soon. If we had this third answer we could predict, from general principles, what the stars ought to be like, and, if our knowledge were adequate and our reasoning sound, our predictions would agree with the facts. As things are, our partial knowledge enables us to interpret many of the most important properties of the stars, though not all.

(4) First Success. The Mass-Luminosity Relation

Let us begin with the equation of state. Since the material is gaseous, we have by the familiar gas laws

$$p = R \rho T/m \qquad (1)$$

(p is the pressure, ρ the density, T the absolute temperature, m the average molecular weight, and R a constant—8.31×10^7 in c.g.s. units.) The density inside a star will be greater at some places, and less at others, than the mean. To get an idea what to expect, suppose we had an imaginary star of the sun's size and mass, and

with uniform density throughout. The pressure at the centre then comes out 9,800,000 tons per square inch, and the corresponding temperature, by the gas laws, is 11,500,000 m degrees Centigrade. Under ordinary laboratory conditions, the molecular weight m would vary enormously with the composition of the gas. But inside the star the atoms must be almost completely ionized, and the heavier an atom is the more parts it is split into. The *average* weight of one of these parts (which is what we need) is 0.5 for hydrogen, 1.3 for helium and about 2 for all the other elements, except the heaviest (which are too rare to be of importance). The general average thus depends almost entirely on the proportion of hydrogen inside the star. We shall see later that there is evidence that this is such as to make the value of m about 1.

For a homogeneous body of M times the sun's mass and r times its radius, the central temperature must be multiplied by $\frac{M}{r}$. If the body is not homogeneous, let x be the ratio of the density at any point to the mean density, and y the ratio of the pressure at this point to the pressure at the centre of a homogeneous sphere of the same size and mass. A very simple calculation then shows that the temperature T is given by

$$T = 11{,}500{,}000 \frac{My}{rx} m. \qquad (2)$$

We can now calculate the temperature at any point inside the star, if we know what it is made of, that is, the value of m, and on what model it is built, that is, how the quantity x varies as we pass from the centre to the surface. (If this is known y can be calculated.)

The density may increase greatly toward the centre, making x very large there, but in this case y also increases. For example, there is a famous "model", discussed by Eddington, in which, at the centre $x = 54$, that is, the central density is 54 times the mean density. But at the same point $y = 93$, so that the temperature is only 1.72 times as great as for a homogeneous sphere. Nearer the surface x and y both fall off, and the temperature decreases. It follows from this that, unless the central condensation is much greater than suggested above, the central temperature of the sun is about 15 or 20 million degrees. A generation ago no one would

have dared to say much about the properties of matter under conditions so far removed from experience. But we know enough about atoms now to be sure of our ground.

At these high temperatures, the flying quanta of radiation, as well as the flying atoms and electrons, tend to drive the atoms which they hit outward and exert a powerful pressure. At 20 million degrees this radiation pressure amounts to 3,000,000 tons per square inch—enough to support a considerable fraction of the gravitational pressure inside a star. This was first realized by Eddington. If β is the fraction of the whole pressure which is carried by the gas, leaving $1-\beta$ for the radiation, he derived the remarkable equation

$$\frac{1-\beta}{\beta^4}=0.0033\frac{\gamma^3}{x^4}m^4M^2 \qquad (3)$$

which enables us to compute the effect at any point in any star. The temperatures previously calculated must be multiplied by β. For the sun's centre (with $m=1$), $\beta=0.97$ for the homogeneous model, and 0.997 for Eddington's model, so that the correction is small. For massive stars, it may be considerably greater.

The outcome of this discussion is that we have gained a good idea of the central temperatures of the stars. The value for the sun is probably 15 to 20 million degrees; for a faint star at the bottom of the main sequence, 12 to 15 million; for a bright star at its top, 25 to 35 million (allowing for radiation pressure). For the giant stars, the values are much lower, about 5 million for Capella and 1 million for a red star at the other end of the group.

For a star built on any given model, we can now find the outward temperature gradient at any point. This, with the opacity of the material, determines the rate of outward flow of heat—and the latter evidently supplies the radiation from the surface, which can therefore be calculated. The opacity arises mainly from the capture of radiation by atoms, which hold it for a moment before they re-emit it, and its law can be determined from the principles of quantum- and wave-mechanics. The researches of Kramers, Gaunt and others have now put the theory of opacity on an apparently reliable basis, though it is not yet exact. Passing over many details, it is found that the luminosity L of a star built on any

model is given by the equation

$$L = C\frac{M^{5\frac{1}{2}}}{r^{\frac{1}{2}}}(m\,\beta)^{7\frac{1}{2}} \qquad (4)$$

where the coefficient C depends upon the model on which the star is built, but does not change rapidly with changes in this.

The equation shows that the luminosity of a star should depend but little on its size, and very greatly on its mass. For large masses, when β begins to diminish, the change is proportionately slower. This is an excellent qualitative description of the mass-luminosity relation, and numerical calculations show that the quantitative agreement is remarkably close. Eddington, who first worked the theory out, determined the constant C (which could not at that time be accurately calculated theoretically), from a single star, Capella, and found that the resulting formula represented the data for all reliably observed stars (except white dwarfs) in an almost uncanny fashion.

Theoretically, a star of given mass may have *any* luminosity, adjusting its size to suit. But to halve L multiplies r by 4, and reduces the surface temperature to 42 per cent. of its original value, so that any large change in luminosity, up or down, would place our hypothetical body outside the observed range of stellar surface temperatures. Within this range a rather small correction (carefully made by Eddington) serves to reduce the observed brightness of a star to the value it would have if shrunk or expanded so that its surface temperature was equal to the sun's. This correction hardly ever amounts to one stellar magnitude, while the observed range in brightness is fully 20 magnitudes.

Changes in the model on which we assume our star to be built do not greatly affect its luminosity. Eddington, Vogt and Biermann have discussed a large number of cases, and found that the effect very rarely exceeds one magnitude. Changes in the mean molecular weight, on the contrary, produce great differences. Recent discussions by Strömgren and Eddington agree in showing that stars of the same mass, size and density-model, differing only in the proportion of hydrogen which they contain, may differ in brightness by a factor of a thousand—more than seven magnitudes. With no hydrogen present, m is about 2, and the central temperature high.

This drives a rapid flow of heat to the surface. As the hydrogen percentage increases, m falls, and so does the internal temperature, while the opacity gradually diminishes. At first the falling temperature prevails, and the luminosity diminishes. Finally, when the gas is almost all hydrogen, the opacity diminishes so rapidly that the escape of radiation becomes greater again. The minimum luminosity is reached with about 85 per cent. of hydrogen by weight. Agreement with the observed brightness is reached at a hydrogen content of 30 to 35 per cent., for the sun, Capella and Sirius, independently. There would also be agreement if about 99¾ per cent. of the gas were hydrogen; but this appears to be less probable. This interpretation of the mass-luminosity correlation is the first great triumph of the theory of stellar constitution. Strangely enough, it is almost *too* successful, for it shows that the observed facts result from very general properties of matter, almost independent of the internal constitution of the stars. Concerning the specific model on which they are built, it tells us practically nothing—but it does give us important information regarding the composition of the interior, which was wholly unexpected. Finally, we may note that this part of the theory does not even suggest why a star of given mass should have any particular size or surface temperature.

(5) Second Success. The White Dwarfs

We have so far assumed that the familiar gas-laws can safely be applied to stellar material, even though it is much denser than any known gas. If the atoms were in their normal condition, this would not be true; they are bodies of known size, and would get jammed together at densities little greater than those of ordinary liquids, so that the material was no longer compressible. But, inside the stars, the atoms are highly ionized, and their remaining fragments, as well as the liberated electrons, are exceedingly small, so that there is no danger of their "jamming" even at thousands of times the density of ordinary matter. The realization of this led to the first intelligible interpretation of the white dwarf stars. It had been known for some time that all the data indicated that their densities must be enormous, but this conclusion was supposed

to be physically impossible till Eddington pointed out that it was a natural consequence of the high ionization.

The later investigations of Fowler, Sommerfeld and other students of quantum theory show, however, that there is a limit to the degree to which a gas can be compressed. Nature abhors overcrowding, though she does not really abhor a vacuum.

Inside an atom the quantum laws provide only two places for electrons close to the nucleus, eight further out, and so on. Similar quantum restrictions apply to the free particles in a gas. Only a fixed number of *slow-moving* particles can be crowded into a given volume—say a cubic centimeter. To get more in we must add faster moving ones. This increases the average energy of a particle, and hence the pressure. Only the excess of the total energy of motion of the particles, above that tied up in this way, is available to count as heat. The lightest particles—the electrons—show this effect of "degeneracy" first. Being very numerous in the stars, they dominate the situation. When degeneracy has gone to the limit, the equation of state is

$$P = K_1 \rho^{5/3} \tag{5}$$

Here K_1 is a constant (equal to $9.16 \times 10^{12} \mu^{-5/3}$, where μ is the average mass per free electron, which is 1 for pure hydrogen, and a little greater than 2 for heavy atoms). This equation is safe to use whenever it gives a considerably higher pressure than the perfect-gas law. For a density 1,000 times that of water, this happens when the temperature is less than two million degrees—while at ten million the gas-law is still a fair approximation. At intermediate temperatures the pressure gradually changes from one value to the other. The exact formula for the change has been worked out, but is complicated.

At extremely high densities, the velocities of the electrons become nearly as great as that of light, and the equation of state becomes

$$P = K_2 \rho^{4/3} \tag{6}$$

where $K_2 = 1.23 \times 10^{15} \mu^{-4/3}$. The transition between this form and the last has also been accurately worked out. It is under way when the density is about two million times that of water.

We can now answer the question, What would become of a star which had lost heat by radiation until all possible sources of internal energy had been exhausted? There would be no more available heat in it, and the matter would therefore be in the degenerate state. The equation (5), together with the law of gravity, then enables us to work out in detail all the properties of the body, since (given the composition, and therefore μ) there are no adjustable constants left. This has been done by Milne. A body of given mass settles down to a definite size and density. With 30 per cent. of hydrogen and a mass equal to the sun's, the radius comes out 1/62 of the sun's, making the diameter 14,000 miles, and the mean density 240,000 times the sun's. The central density is six times as great, or two million times that of water.

Smaller masses are of larger diameter—being less compressed by their own gravitation—so that the volume is inversely proportional to the mass. For large masses, the central density is so high that equation (6) becomes applicable. The compressibility increases, and the size of the body becomes still smaller. For masses greater than twice the sun's, practically the whole interior is in the second stage of degeneracy. The law of this state no longer assigns any limit to the possible contraction and any greater mass would presumably shrink until the protons and electrons themselves were "jammed". The resulting density can only be roughly guessed, but it is probably many billions of times the sun's, so that the shrunken mass would be only a few hundred miles in diameter!

Such bodies, whatever their masses, would be dead stars—cold on the surface, and quite invisible. But a star may be nearly but not quite dead, retaining a small amount of internal heat. In the deep interior this would contribute in but small proportion to the total energy and pressure, so that the inside of the star would be built very much as has been described. Towards the outside, there would be a gradual transition to more familiar conditions, and the degenerate core will be surrounded by an envelope of ordinary gas. The outer diameter should be larger, but not much larger, than has just been computed. The internal temperature will be much lower than that of a non-degenerate star, and hence the luminosity will be much smaller for a given mass than that of a

normal star. Since the surface layers are composed of ordinary gas, the spectrum will differ little from that of a normal star.

Now these are exactly the properties which are actually exhibited by the white dwarfs, and there is no longer any doubt that these actually have degenerate centres. Milne points out that we should have not only white dwarfs with degenerate cores, but still fainter orange and red dwarfs, stages of approach to the dead "black dwarf". Such stars should be excessively faint, and only the very nearest of them would have any chance of being observed.

Of the few white dwarfs for which good data are available, four, by great good fortune, are components of visual binaries, and we can find their masses. These range from 0.85 to 0.37 times the sun's mass, and all lie within the interval for which even a completely degenerate mass finds a limit set for its contraction. It is possible that we do not find white dwarfs of large mass, because any such objects, if they existed, would be of such excessively small size that we could not see them at stellar distances, whatever their surface temperature.

A degenerate gas is known to be highly transparent to radiation. Hence, as Milne points out, the differences in temperature within it must be relatively small. The layer of non-degenerate gas near the surface is much more opaque, and acts as a blanket to keep the interior warm. Milne estimates that the temperature in the interior of the companion of Sirius does not exceed 15 million degrees.

The white dwarfs have, within the last few years, changed their rôle from most perplexing to the best understood class of stars. The present theory of their nature (which we owe to Milne) is the second notable triumph of the application of general physics to stellar constitution.

The properties of gas masses with degenerate cores have been the subject of lively discussion during the last couple of years, and a great deal of work has been done on the subject—notably by Milne and his colleagues at Oxford. To save a great deal of algebraic labour, he has worked on the assumptions that the rate of liberation of energy is uniform all through each mass (though differing from one mass to another), and that the opacity is constant in the gas phase, and also in the degenerate state, though much

smaller. The transition between the two states is supposed to be sharp, but without discontinuity.

These assumptions do not lead to a close numerical representation of the properties of actual stars; for example, they give a change of luminosity with mass which is similar to, but only about 60 per cent. as great as, the actual change. However, they were not designed for this purpose, but to enable an exhaustive survey of the consequences of at least *one* set of assumptions to be made. The problem remains difficult, but Milne has solved it by methods of great mathematical elegance.

The results are interesting. For bodies of small mass (less than about twice that of the sun), the size and brightness steadily diminish as the degenerate core grows larger. For large masses, the brightness increases slightly until the core is of about a quarter of the star's diameter, and then falls off. There is no great loss of light (exceeding a magnitude) until the core occupies most of the volume. All these configurations, except a few of very large mass, are smaller than those in which the centre is just beginning to be degenerate. The latter diminish slowly, with increasing mass, from the size of Saturn to a little smaller than Uranus. The final completely degenerate forms are from one third to one fifth as big.

Milne has not yet extended his calculations to include the second stage of degeneracy, but it is clear that this would make the radii still smaller. His calculations, therefore, appear to represent transitions between ordinary stars and white dwarfs.

Professor Milne has expressed the opinion that the exact solution of certain equations might lead to much larger computed diameters, and hence to an explanation of main-sequence stars, and even giants, as bodies possessing dense, degenerate cores; but later calculations by Cowling are unfavourable to this view. If, however, Kramers' opacity law is substituted for the simpler assumption, keeping the same law of energy generation, Jeans has shown that bodies of large mass must inevitably be greatly concentrated toward the centre. Further computations on this basis are to be desired; meanwhile the question whether actual stars (other than white dwarfs) may have degenerate cores must remain open.

(6) Sources of Stellar Energy Synthesis or Annihilation of Atoms

So far we have considered only the escape of heat from a star, without inquiring how the supply is maintained. The rate of loss is almost incomprehensibly great. We can come nearest to realizing it by remembering that, according to the theory of relativity, heat, like other forms of energy, possesses mass. It is as proper to speak of a pound of heat as of a pound of ice; but a pound of heat is a very large amount—enough, in fact, to melt 30 million tons of rock and turn it into white hot lava. The sun radiates heat away into the depths of space at the rate of 4,200,000 tons per second—and the sun is a smallish star! Upon what vast stores of energy can it draw to keep going?

The first approximately adequate suggestion was made by Helmholtz, and developed by Kelvin. All parts of the sun attract one another strongly. If it was once larger than now and has contracted to its present size, the gravitational forces must have done an enormous amount of work during the contraction, which would necessarily reappear as some other form of energy. Part of this is doubtless still stored as heat in the interior. The rest, escaping to the surface, would maintain the radiation. The whole supply made available by contraction from a very large size may be calculated easily, though not exactly, since it depends on the way in which the density increases toward the centre. On the most liberal assumptions regarding this it would suffice to keep the sun shining at its present rate for about 20 million years. Before the great extent of geological time was realized, this appeared to be an adequate explanation. But now we have conclusive evidence that the earth's surface has had very nearly its present temperature for 1,000 million years or more, which means that the sun has been shining about as strongly as at present through all these ages. Some greater supply must be sought, and the only present hope is in changes in the atoms themselves, involving a loss of mass.

(To be concluded)

NOTES AND QUERIES

Communications are invited, especially from amateurs. The Editor will try to secure answers to queries.

Two New Meteorites

The first fell July 1, 1933, within a few feet of a church at Cherokee Springs, South Carolina. It is a stone and weighs about twelve pounds. The fall was observed by two intelligent men, who state that the stone, which was picked up immediately, was too warm to hold comfortably in the hand, though not hot.

It is roughly rectangular in outline, bounded by rather flat surfaces showing a rather striking absence of the usual pitting. A considerable broken area at one end shows it to be apparently a light gray spherulitic chondrite, with very strongly developed chondrules and conspicuous inclusions of troilite. One or two smaller broken spots show traces of a secondary fusion crust. The primary crust is for the most part intact and more than ordinarily thick.

The second meteorite fell about six miles west of Athens, Alabama, at about 9.30 a.m., on July 11, 1933. Mr. W. R. Hardiman, a farmer, with his son were working in a field when their attention was attracted by a peculiar humming or singing noise, like an airplane flying high. The noise grew louder, in their opinion for five minutes, then changed to a whizzing noise and ended in a swish and a thud. The object landed within thirty feet of the son. He walked over, expecting to find an object weighing a hundred pounds, but found a small hole, perhaps five inches across and five inches deep, with a small dark stone in it. The stone had fallen vertically, as nearly as he could tell. He did not, however, touch it until his father arrived from a more distant part of the field. The little stone, weighing about nine ounces, was then removed and found to be noticeably warm, but not hot.

The above descriptions are by Stuart H. Perry, of the Adrian *Daily Telegram,* Adrian, Michigan. There is a picture of the second meteorite with a fuller account in *Popular Astronomy* for October.

The Adler Planetarium

A well-written and fully-illustrated book describing the Adler Planetariam and Astronomical Museum, prepared by the director,

Professor Philip Fox, has just been published. There are 62 pages, 6½ x 10 inches, in an attractive board cover. This planetarium at Chicago, the first in America, was opened on May 12, 1930. The second is at Philadelphia, and will begin operations in November. During the first year the attendance at the Adler planetarium was 731,108, and the average daily attendance for the first two years was 1,704. During the first hundred days of the Exposition this summer there were 550,000 visitors, and during the last half of August the daily attendance averaged over 10,000. For a time there were 20 demonstrations per day; latterly, 19. The regular staff consists of Professor Fox, Miss Bennot and Mr. F. W. Schlesinger; but during the summer the following assisted: J. C. Duncan, Dinsmore Alter, John Pitman, D. W. Morehouse, Walter Bartky, H. S. Everett, John E. Merrill and H. E. Crull.

In the book are numerous pictures of objects in the astronomical museum. There are many remarkable old instruments, the majority of them belonging to a large collection which had been in the possession of Ant. W. M. Mensing of Amsterdam, and which was purchased by Mr. Adler. The institution is one of the attractions of Chicago and has aroused much interest in astronomy. Let us quote the last paragraph in Professor Fox's guide:

"Here is a museum devoted to the noblest aspiration of man's mind, the understanding of the universe. Here he may let his mind grope outward into limitless space nor remain forever earthbound, shrinking the universe to his petty stature. Better be again a clod of clay of that Earth from which he came than never to have risen to the height from which the wide vision of creation may be obtained and have felt that glorious exaltation of him who cried, 'Then felt I like some watcher of the sky'."

The Leiden Observatory

During the month of October occured the celebration of the 300th anniversary of the foundation of the Leiden Observatory and also the 25th anniversary of the appointment of Dr. W. de Sitter as professor at Leiden. It is fitting that a short history of the Observatory should be published. It was prepared by Dr. de Sitter and contains 48 pages. In it are portraits of Jacob Gool, the founder; Willebrord Snell (1625), famous for his law of refraction; Frederik Kaiser (1862), and H. G. van de Sande Bakhuyzen (1908), well

known as directors. There are also illustrations of the buildings and some of the instruments. At present the equipment is extensive while the members of the staff number 31. The observatory has had a very honourable record and many well-known names appear in the booklet. What will some of our modern American observatories be like three hundred years hence?

A Fireball Seen in Toronto, September 24, 1933

Mr. J. Whitehouse, of 249 Roehampton Ave., Toronto, gives the following description of a fireball:

At 8.40 p.m. on Sunday evening, when facing north, I saw a very large meteor or fireball fall almost vertical but slightly inclined towards the west. It appeared to come from about the middle of the Dipper, which was low in the northern sky. It was about four times as large and bright as any of the other heavenly bodies, with the exception of the moon. It was silvery or creamy white. There was a very short pear-shaped tail and sparks seemed to shoot out from it on all sides. Its fall took only about two seconds, as it had not far to go before passing below the horizon at a point about 20 degrees west from the true north. I was standing on high ground at the time and watched it fall quietly below the sky line. The night was very clear.

Audibility of the Aurora

In *Science* for September 8, 1933, Clark M. Garber gives the following evidence regarding the much debated subject of the audibility of the aurora:

The proposition of the audibility of the aurora borealis has been the subject of considerable speculation and much doubt. Some scientists have claimed with much positiveness that the aurora emits no audible sounds and that the beams of light or electrical waves, such as they may choose to call them, do not come close enough to the earth's surface to be audible, even if any sound were emitted. In my own mind there can be no doubt left as to the audibility of certain types of aurora, for I have heard them under conditions when no other sound could have been interpreted as such, for no other sounds were present.

From the Eskimos I first learned that the aurora could be heard and, like most people, was rather skeptical about it, believing that their statements were based to a great extent on their superstitions. I was told by some of

the older Eskimos that when the aurora displays become audible they are able to imitate the sound by whistling in such manner that the beams of light will be attracted or drawn down to them. This, of course, is purely superstition. However, it does bring out the fact that the Eskimos were frequently able to hear the aurora.

The following is my own personal experience which convinced me that the aurora borealis was actually audible. In the winter of 1925-1926 I was engaged in making a drive of reindeer across the mountain range bordering the Arctic coast north of Cape Prince of Wales on Bering Strait. One night during this drive found me travelling by starlight across the divide at the head of Nuluk River. This divide has an elevation of approximately two thousand feet. It was two o'clock in the morning when my native driver and I broke camp in order to overtake the reindeer herd ahead of us. As we climbed with our dog team to the summit of the divide we were both spellbound and astounded by the magnificent display of aurora, the most wonderful display I have ever witnessed during my eight years of life among the Eskimos.

Great beams of light shot up from the northern horizon as if a battery of gigantic searchlights were searching the arctic landscape. In front of these beams and throughout the whole length of the northern horizon great waves of iridescent light travelled from west to east like gigantic draperies before the stage of nature's amphitheatre. Great folds or waves, ever changing in colour, travelled one after another across the horizon and from behind them streamed the powerful beams of white light. These beams of light could be seen passing directly over our heads, and when one chanced to come over the divide it appeared to be not more than a hundred feet above the surface. The spectacle was so awe inspiring that the dog team was stopped and I sat upon the sled for more than an hour absorbing the marvellous beauty of this most unusual display. As we sat upon the sled and the great beams passed directly over our heads they emitted a distinctly audible sound which resembled the crackling of steam escaping from a small jet. Possibly the sound would bear a closer resemblance to the cracking sound produced by spraying fine jets of water on a very hot surface of metal. Each streamer or beam of light passed overhead with a rather accurate uniformity of duration. By count it was estimated to require six to eight seconds for a projected beam to pass, while the continuous beam would often emit the sound for a minute or more. This particular display was so brilliant that traces could easily be seen long after daylight.

CLARK M. GARBER.

CONDUCTION OF ELECTRICITY THROUGH GASES

Faraday made a good beginning, but for some reason or other relinquished this field of research. It was not properly developed until the eighteen-sixties and the eighteen-seventies. We ought first

to remember the name of the man who made the tubes, for in 1860 the injunction "seal the electrodes into a tube" was not so easy to obey as now. This man was an itinerant glass-blower who earned his living by wandering from college to college in Germany and blowing such glassware as the professors of chemistry and physics might happen to want; his name was Geissler. In Bonn he found a professor [Plücker] who wanted low-pressure discharge-tubes for spectroscopic purposes, as the science of spectroscopy was then just coming into being. Reserving the spectra for himself, this professor turned over the task of studying the electrical properties of the discharge to one of his pupils. This pupil, whose name was Hittorf, obtained the chair of chemistry and physics in a small and half-starved college [Münster], where he stayed for fifty years. In 1869 he published the first of his great papers; I will quote its opening sentence: "The darkest part of the science of electricity to-day is incontrovertibly the process by which current is conducted through gases." Nowadays we should say just the opposite, and for that we should thank Hittorf; and also Crookes, and others after them, but Hittorf first of all.—K. K. Darrow in *Science*.

C. A. C.

MEETINGS OF THE SOCIETY

AT VANCOUVER

July Outdoor Meetings.—The first garden meeting was held on Saturday evening, the 15th, at the residence of Mr. H. P. Newton, Telford Ave., Burnaby, where Mr. Newton's equipment was examined and some observing carried out. About 25 people attended. The most interesting instrument was a fine 5¼-inch equatorial refractor constructed by Sir Howard Grubb, the noted English maker. Mr. Newton's 3-inch refractor was also available and later Mr. McGrath brought his 3-inch Zeiss refractor.

The sky was clear and visibility good, but seeing conditions corresponded to no more than about 5 of the 10-point scale suggested by Pickering, which state of affairs, however, is not to be despised in the usually turbulent atmosphere of these parts. Jupiter was first observed but its low position in the western sky did not permit of first-class views. There being no other planets visible, several double stars were observed under various powers.

Mrs. Newton very kindly provided an agreeable refection after which the party looked over a number of beautiful drawings of planetary detail, done by Mr. Newton in the course of his long observing experience.

Mr. Teasdale expressed the thanks of the group for a meeting which was much enjoyed by everyone, not forgetting a few mosquitoes who entered into the proceedings with quite unnecessary spirit.

A second garden meeting was held on the evening of the 22nd at the residence of Mr. J. Teasdale, and was attended by about 30 people. The equipment consisted of an excellent 6-inch Newtonian reflector constructed by Mr. Teasdale.

The sky was clear and visibility and seeing conditions very good, the latter being estimated at 7 to 8 on Pickering's scale.

Observations were made of Mars and of Jupiter, during which a satellite was occulted by the planet. The telescope was then turned on the Mizar and Alcor group, followed by observation of the double-double Epsilon Lyræ, Beta Cygni, and the cluster in Hercules, in which a number of the individual stars were faintly defined. Zeta Bootis, a close double of 1″.05 separation was resolved with power of 190. Later Saturn rose to fair position and good views were obtained, Cassini's division of the rings being well seen and glimpses obtained of the crape ring. Refreshments were provided through the kindness of Mrs. Teasdale.

The third garden meeting was held at the residence of Mr. C. E. McKenzie with an attendance of about 20. The equipment consisted of a 7.3-

inch Newtonian reflector with equatorial mounting, constructed optically and mechanically entirely by Mr. McKenzie. Visibility was good but seeing only average. During the early part of the evening good views were obtained of the moon's first quarter. Saturn was examined later but seeing was not good enough for best results. The same difficulty prevented good observation of any double stars. Mr. McKenzie very kindly served refreshments after which many members inspected Mr. McKenzie's finely equipped workshop.

September 12, 1933.—The seventeenth regular meeting of the Vancouver Centre was held at the University of British Columbia. The president, Mr. Teasdale was in the chair.

The president first welcomed the members to another season of activity, and made some announcements about the programme of meetings for the year.

Dr. G. M. Shrum then gave a short talk on the progress of the construction of the Dunlap Observatory at Toronto. While in the east this summer, he visited the site of the observatory as well as the plant of the Corning Glass Company where the disc for the 76-inch mirror is being cast from Pyrex glass. The observatory is being presented to the University of Toronto by the widow of the late Mr. D. A. Dunlap.

Dr. Shrum then described the unusual honeycomb contsruction of several discs for mirrors being produced for Mount Wilson, including that of diameter 200 inches, and showed slides of the equipment to be used in the pouring and annealing of the 76-inch disk.

The Adler Planetarium in Chicago was described by Mr. J. R. Pollock who has recently returned from the east. His first impressions of Chicago were given in an interesting contrast of the Loop District with quiet dignity of Madison Avenue.

The Planetarium, which was opened in 1930, is housed in a circular building 70 feet in diameter, forming the centre of an artistic grouping of sculpture symbolical of astronomy. Within the dome there is a complete representation of the sky both northern and southern hemispheres produced by means of a complicated projection apparatus at the centre.

Mr. Pollock gave a detailed description of the construction of this projection machine, which enables the diurnal motion of the stars as well as the relative motions of the planets and the moon to be reproduced with astonishing perfection of detail.

The meeting then adjourned to the campus, where Prof. A. Lighthall directed a survey of the sky, tracing the main constellations visible and locating the principal component stars. The seeing was not of the best, but the interest shown indicated that to most of the members this survey provided most valuable instruction.

WILLIAM URE, *Recorder.*

AT LONDON

October 13, 1933.—The first Autumn meeting was held in the London Life Building, Mr. Geo. Gunn, the president, in the chair. A quarter hour was spent on the roof learning the constellations. The telescope used showed two moons and the unbroken ring of Saturn.

The president introduced to the members three books read during the summer, from one of which "Life's Place in the Cosmos" he read some interesting paragraphs. He then introduced the speakers of the evening, Dr. H. R. Kingston, whose subject was: Saturn, the Gem of our Solar System.

Up to the time of Sir Wm. Herschel (1781) this planet was thought to mark the limit of our system. Dr. Kingston traced the progress of men's knowledge of Saturn from the time Galileo recognized something peculiar about the body and at first considered it a sphere with a smaller one on each side of it. When, through succeeding years, these "ears" were seen to become smaller, vanish, grow again and expand, the idea of a ring surrounding Saturn took the place of the triple-planet notion. The ring at first was thought to be solid, but is now known to be made up of a multitude of small moons, each following its own path around the planet at varying rates of speed.

Through a good telescope, the ring is seen to be divided by a dark circle called Cassini's division, from the name of the discoverer, and the outer half is again divided by fainter rings. There is also a ring of greyish matter known as the crape ring.

Besides its rings, Saturn has nine moons, but in spite of all these bodies reflecting the sun's light, the radiance from them is only a small part of what we receive from our moon, on account of Saturn's great distance from the sun.

The planet is next in size to the giant Jupiter but its specific gravity is less than water. Its temperature is about 250° below zero.

The composition of the planet is a mystery as the spectrum shows lines corresponding to those of no known material.

N. Morris, *Secretary-Treasurer.*

ASTRONOMIC DISPERSION

I like the twinkling stars,
Brilliant Jupiter and Mars,
The comets, and Saturn, and the hazy nebulae.
Chromatic aberration,
Planetary perturbation,
Sun-spots, coronas, and the solar faculae.

From the zenith to the nadir,
On the lunar terminator,
The shadows slowly hide the icy peaks.
Old astronomers in satin,
Studied objects named in Latin,
And were stunned by these celestial freaks.

Spectroscopes are quite amusing
When it comes to light diffusing,
It is really quite the thing for observation.
It is just a simple prism,
A man-made organism,
Which determines heat and speed in radiation.

Some say the sun is hot,
But in sun-spots it is not.
Spectrograms will show it's really cooler there.
As they churn in whirlpool fashion,
There is north and south attraction,
Which disturbs the pale corona's mystic glare.

Wonderful amazing comets,
Move in parabolic orbits,
With their fiery tails astreaming 'cross the sky.
And the rings of distant Saturn,
In a clever coloured pattern,
Is a sight thats very pleasing to the eye.

Whither comes and goes the race
In this endless living space,
Is the question modern men of science probe.
As for me, I'll be archaic,
Being modern and prosaic,
Duly thankful that I'm living on this globe.

Bob Ball, U. of M., 1933.

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